

REVIEW OF HANDLING AND USE OF FGD MATERIAL

CARRC Topical Report

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CARRC Final Report

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REVIEW OF HANDLING AND USE OF FGD MATERIAL

INTRODUCTION

Flue gas desulfurization (FGD) material is one of the “four large-volume wastes from the combustion of coal by electric utility power plants” as defined by the U.S. Environmental Protection Agency (EPA) (Federal Register; Code of Federal Regulations, Part 261, Title 4). FGD material is produced from the capture or scrubbing of sulfur dioxide (SO₂) emissions using a sorbent. FGD technologies were developed and refined to aid coal-fired power plants in achieving emission reductions of SO₂ mandated in the 1990 Clean Air Act Amendments (CAAA).

In 1987, the American Coal Ash Association (ACAA) reported that 14.2 million tons of FGD material was produced in the United States. In 2000, that number nearly doubled to 26 million tons. In 1987, only about 1% of the FGD material produced was utilized, but in 2000, nearly 20% of the annual production was utilized. Despite the large increase in utilization, FGD material still remains a vastly underutilized, valuable material. Emission control regulations generally have a direct impact on coal combustion byproduct (CCB) production, and while EPA “encourage[d] the utilization of coal combustion byproducts and support[ed] State efforts to promote utilization in an environmentally beneficial manner,” federal actions are expected to impact the volumes of FGD material produced annually in the United States and potentially some management options for CCBs including FGD material. In fact, the annual production of FGD material is predicted to increase significantly in coming years as the number of FGD systems is expected to double in the next 7 years in response to new emission regulations (Government Panel, 2001). This production increase in FGD material, coupled with future federal guidance on the disposal and mine placement of CCBs, including FGD material, may have a significant impact on utility CCB managers and others involved in CCB management.

The purpose of this report is to provide information on the state of the FGD production; advantages and disadvantages of various FGD systems and materials; chemical and physical characteristics of FGD materials; current practices for handling, disposing, and utilizing these materials; and other information for those interested in CCB management.

BACKGROUND

Emissions from electric generating facilities, such as SO₂, NO_x, and mercury, can cause detrimental impacts to human health and the environment. Although concentrations are low, electric generation facilities account for the majority of SO₂ and mercury emissions in the United States. The major health concerns associated with exposure to high ambient concentrations of SO₂ include breathing difficulty, respiratory illness, and aggravation of existing cardiovascular disease. In addition to health impacts, SO₂ leads to acid deposition in the environment. This deposition causes acidification of lakes and streams and damage to tree foliage and agricultural crops. Furthermore, acid deposition accelerates the deterioration of buildings and monuments (Srivastava and Jozewicz, 2001). Atmospheric mercury concentrations are usually low and of

little direct concern; however, atmospheric mercury contributes to the mercury loading in surface waters where it can bioaccumulate in fish and animal tissue in the form of, methylmercury (EPA, 1998).

The CAAA were designed to reduce SO₂ and NO_x air emissions. No mercury control policies from electric facilities are specified in the CAAA. Mercury emission reductions reflecting lower mercury release than available from coal are due to emission control technologies for other pollutants, such as SO₂ and NO_x, that can also incidentally capture mercury. Currently, emission control technologies are fairly broadly applied for control of particulate, SO₂, and NO_x from coal-fired power plants. U.S. utilities generally employ one of two strategies to control SO₂ in the flue gas stream: 1) FGD units or 2) compliance fuels. Particulate control is typically accomplished by the use of fabric filters (also called baghouses or electrostatic precipitators [ESPs]). NO_x is typically controlled through low-NO_x burners, overfire, selective catalytic reduction (SCR), selective noncatalytic reduction (SNCR), or a combination of these technologies. Particulate NO_x control technologies will not be discussed in this report except in relation to the issue to SO₂ control. Other methods including fluidized bed combustion (FBC) units can also control SO₂. Many western coals and some eastern coals are naturally low in sulfur and can be used to meet SO₂ compliance requirements. Utilities may also physically clean or wash all or part of the fuel prior to combustion. Physical coal cleaning at the mine, transshipment point, or power plant is quite widespread in the United States not only because it reduces emissions, but also because an increase in steam generator efficiency is often possible if the fuel feedstock can be made more homogeneous. Utilities may also blend coals of different sulfur contents to achieve a mix that is in compliance with applicable regulations. Most utilities, approximately 70%, utilize compliance fuel to achieve the SO₂ emission levels currently mandated. According to the U.S. Department of Energy (DOE, 1997), FGD scrubbing unit utilization is estimated to cost \$322 per ton of SO₂ removed and is the most expensive compliance method, although costs vary widely across regions. Also, according to DOE, modifying a high-sulfur bituminous coal-fired plant to burn lower-sulfur subbituminous coal is estimated to cost \$113 per ton of SO₂ removed and is the least expensive method. Although FGD scrubbing units are the most expensive compliance method, FGD can be cost-effective. The type of compliance method implemented needs to be carefully evaluated for the specific coal-fired plant.

Approximately 22% of utilities in the United States utilize FGD systems to achieve the currently mandated SO₂ emission levels. This percentage is expected to double in the next 7 years in response to emission regulations (Government Panel, 2001). FGD systems can be classified as either wet or dry systems, and both systems produce a byproduct generically referred to as FGD material. FGD material is a high-volume byproduct included by EPA as one of the four high-volume CCBs in its 1993 RCRA (Resource Conservation and Recovery Act). The four high-volume CCBs (fly ash, bottom ash, boiler slag, and FGD material) are designated as solid wastes under RCRA Subtitle D as a result of RCRA. In the second phase (Government Panel, 2001) of the evaluation, EPA supported this determination.

Nearly 26 million tons of FGD material was generated in the United States in 2000, but less than 20% of that production was utilized according to the ACAA statistics on “Coal Combustion Product Production and Use” (ACAA, 2001). These statistics do not differentiate

between FGD material generated from wet or dry FGD systems, but a review of existing FGD systems indicates that wet FGD systems are the preferred control technology, accounting for over 80% of the total FGD capacity worldwide (IEA, 2000).

DISTRIBUTION OF FGD SYSTEMS

Coal-fired power plants in the United States and Japan began using FGD equipment in the early 1970s. Western Europe followed in the 1980s. In the 1990s, the application of FGD became more widespread and today includes countries in central and eastern Europe, Asia, and elsewhere. Today, there are approximately 1140 coal-fired power plants in the United States. The states generating the bulk of the FGD material in 1996 were Texas, Kentucky, and Indiana, accounting for almost 50% of total FGD material produced (Kalyoncu and Matos, 1997). An illustration of FGD generation by state is included in Appendix A.

According to the IEA Coal Research, the most widely used FGD systems in the world are wet scrubbers using calcium-based sorbents (IEA, 2000). Initially, these systems produced nonusable residues; however, systems producing a salable byproduct are now preferred. Wet FGD systems are currently installed on about 25% of the coal-fired utility generating capacity in the United States, representing about 15% of the number of coal-fired units (McDonald, 2000). Spray dry scrubbers and sorbent injection installations are growing in use in the United States and Europe, especially on small units. Despite their potentially high-value byproducts, these processes have achieved only limited use. Figure 1 illustrates the number of wet and dry systems in the United States and worldwide.

Other types of SO₂ removal technologies, such as FBC systems, can be effective. FBC is a dry process that is primarily installed on smaller-scale industrial systems because FBC units are effectively installed as a separate system. The system mixes the coal with a sorbent such as limestone or other bed material. The coal and bed material mixture is fluidized during the combustion process to allow complete combustion and removal of sulfur gases. The ash is collected in the flue gas using a baghouse or ESP, and the bed residue is removed from the bottom of the boiler.

COMPARISON OF FGD SYSTEMS

FGD technologies use an alkaline slurry to absorb SO₂ in the flue gas, producing sodium or calcium-sulfur compounds. According to Srivastava (2001), commercially available FGD technologies can conventionally be classified as once-through and regenerable, depending on how the sorbent is treated after it has sorbed SO₂. In once-through technologies, the SO₂ is permanently bound by the sorbent. In regenerable technologies, the SO₂ is released from the sorbent during the regeneration step and may be further processed to create sulfuric acid, elemental sulfur, or liquid SO₂. Both the once-through and regenerable technologies can be further classified as wet or dry, depending on if the reagent is wet or dry when it leaves the absorber. New FGD processes, especially those combining SO₂ and NO_x removal, are continually being developed and are discussed further, later in this report.

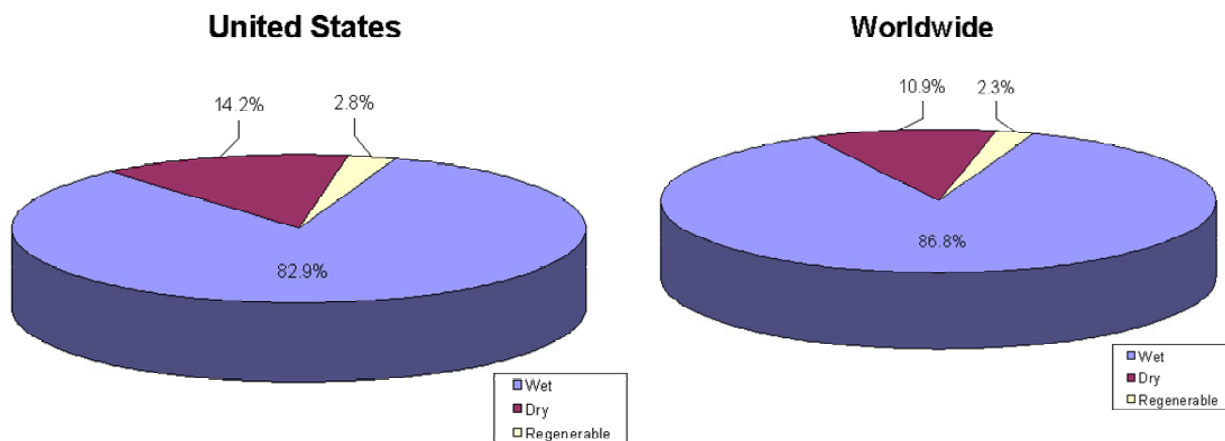


Figure 1. Comparison of wet–dry and regenerable FGD systems.

Wet FGD Systems

Wet FGD systems are the most widely used FGD technology. The use of a widely available and inexpensive sorbent (limestone), production of a usable byproduct (gypsum, calcium sulfate dehydrate, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), reliability, availability, and most importantly, the efficiency achievements that can be as high as 99% are the incentives behind the popularity of this technology especially at large-scale utilities. In 2000, 87% of FGD systems in the world were wet systems; this number is expected to increase even more as emission regulations are adopted. Although capital costs are higher with this technology, operating costs are lower, making this system very cost effective. Also, the production of a valuable gypsum byproduct contributes toward reducing operating costs. Wet limestone scrubbers, which produce a mixture of calcium sulfate/sulfite and fly ash, have a smaller share of the market compared to the gypsum-producing processes. The disposal costs of the byproducts are discouraging the use of this technology in countries where disposal sites are unavailable or regulation prohibits it. In the United States, several plants have converted their wet lime/limestone waste plants to gypsum-producing facilities, and this trend is expected to continue (Soud, 2000).

Limestone-Forced Oxidation

The limestone-forced oxidation process, which minimizes scaling problems in the absorber, is the preferred FGD technology worldwide. This technology involves recirculating a slurry of limestone and water through absorbers where it absorbs SO_2 in the flue gas. Air is bubbled through the calcium sulfate–sulfite slurry to form gypsum. The byproduct dewateres easily and results in less wet waste volume. This process is a proven technology that has been used extensively in the United States and can achieve nearly complete oxidation. There are more than 10 active suppliers available for this process. The process performs best with medium- to

high-sulfur coals and does not respond quickly to load change. Economically, this process uses a low-cost reagent and consumes between 1.6%–1.8% of gross power (Miller, 2002).

Limestone-Forced Oxidation/Organic Acid

This process is the same as the limestone-forced oxidation process described above except that it adds an organic acid to the slurry to increase the limestone dissolution rate which results in a higher SO₂ removal (Miller, 2002).

Lime Dual Alkali Process

This process uses sodium sulfate solution as an absorbing agent that is recirculated through the spray tower to remove SO₂. The spent solution is mixed with lime in a separate process loop simultaneously forming a calcium sulfite sludge while regenerating the spent sodium sulfite solution. Advantages of this process are lower corrosion and erosion and less scaling and plugging. Disadvantages include the high cost of lime and soda ash reagents. Currently, there is no supplier for this technology in the United States (Miller, 2002).

Magnesium-Promoted Lime

Either a magnesium-enhanced lime (typically 5%–8% magnesium oxide) or dolomitic lime (typically 20% magnesium oxide) is used in this process. This slurry is more reactive than limestone slurry but is also more expensive (Srivastava, 2000). The lime slurry is fed to the spray tower to form a calcium sulfite sludge, which also contains a small amount of magnesium sulfite. If forced oxidation external to the absorber is used, the quality of the gypsum will be improved. Commercial-grade gypsum produced from this process is brighter than that from conventional wet systems, resulting in a higher commercial value (Srivastava, 2000). Advantages to this system include a lower liquid-to-gas ratio and reduction in scaling and plugging. It is estimated that there are from three to five suppliers for this process (Miller, 2002).

Seawater Processes

The seawater processes use the natural alkalinity of seawater to neutralize SO₂. The chemistry of the process is similar to the limestone-forced oxidation chemistry except the limestone comes completely dissolved with seawater and the chemistry does not involve any dissolution or precipitation of solids. The sulfate is completely dissolved in seawater so as a result, there is no waste product to dispose of (Srivastava, 2000). This process has achieved limited use.

Sodium Scrubbing Process

The primary absorbing material for this wet system is a sodium sulfite solution that is recirculated through the spray tower to remove SO₂ in the flue gas stream. Sodium carbonate is used as the reagent. Like the lime dual alkali process, the advantages of this process are lower corrosion and erosion and less scaling and plugging. A disadvantage is the high cost of soda ash

reagents. This system has been proven at several locations in the United States; however, there currently are no suppliers of this technology (Miller, 2002).

Ammonia Scrubbing

This process is similar to other wet technologies except it uses highly reactive ammonia as a reagent. Ammonium hydroxide reacts with SO_2 to form ammonium sulfite, which is oxidized to ammonium sulfate. This technology can provide SO_2 removal greater than 95%. This process is also capable of removing other acid gases such as sulfur trioxide and hydrogen chloride (Srivastava, 2000).

Marsulex Environmental Technologies (MET) is the major promoter of this technology. Alstom and Lurgi also have a version of this technology (Miller, 2002). According to MET (Walsh, 1999), this technology works best with power plants that match the following profile:

- High fuel cost
- Low load factor
- Proximity to navigable water or good rail access for pet coke, ammonia, and ammonium sulfate transportation
- Preferably in location with high ammonium sulfate prices

MET's patented technology claims it enables the use of low cost, 5%–7% sulfur fuels without the associated sulfur penalty.

The greatest benefit of this technology is that its high-value byproduct, ammonium sulfate, can be sold as fertilizer. It is important to note that the value of this product will depend largely on the market and product quality has been an issue of concern in the past. MET suggests that for every ton of ammonia utilized, approximately four tons of ammonium sulfate is generated (Walsh, 1999). MET's technology is currently installed on the Dakota Gasification Plant in Beulah, North Dakota. Two additional installations are planned for the Santee Cooper Facility in South Carolina and the Mildred Lake Oil Sands Facility in Alberta, Canada (Marsulex, 2001)

Dry FGD Systems

Dry FGD systems are the second-most widely used FGD technology. This technology is considered efficient and reliable and has lower capital costs than wet scrubbers. However, its operating costs are higher because of the use of a more expensive sorbents. In addition, most byproducts from this technology cannot be utilized and need to be disposed of because they are usually made of a mixture of calcium sulfite, calcium sulfate, and fly ash (Soud, 2000).

Lime Spray Drying

The process consists of mixing hot flue gas in a spray dryer vessel with a mist of finely atomized fresh lime. The SO₂ in the hot flue gas reacts with the sorbent as the water in the slurry evaporates. The dried solids are collected in the bottom of the vessel in a particulate control device. This technology is most often used for power plants that are 550 MW or larger that burn low-to-medium-sulfur coal, between 0.4% and 2%. An average of 90% SO₂ removal can be achieved (EPA, 2002b). The resulting FGD material is frequently referred to as spray dry ash or material and is a calcium sulfite-rich material.

Duct Sorbent Injection (DSI)

DSI is intended to enable SO₂ control directly in the flue gas duct between the air preheater and the particulate control device. Hydrated lime is typically used as a sorbent, and occasionally sodium bicarbonate is used (Srivastava, 2000).

Furnace Sorbent Injection (FSI)

In the FSI system, a dry sorbent is injected directly into the furnace in the optimum temperature region above the flame. Because of the high temperature (approximately 1000°C), sorbent particles decompose and become porous solids with high surface areas (Srivastava, 2000).

Circulating Fluidized Bed

In this system, a dry sorbent, most often Ca(OH)₂, is contacted with humidified flue gas in a fluidized bed. The combustion fluidized bed provides a long contact time between the sorbent and flue gas has because the sorbent passes through the bed several times (Srivastava, 2000). The solids are collected in an ESP or baghouse. A larger particulate collector may be needed to maintain the required particulate emission levels compared with a non-circulating sorbent.

This process is not widely used in the United States, and is primarily used in Germany for units ranging from 50 to 250 MW (Srivastava, 2000).

FGD MATERIAL CHARACTERISTICS

According to an IEA Coal Research (Clarke, 1993) study, differences between mineralogical, chemical, and physical characteristics of FGD material, from both similar and different technologies, can be attributed to a combination of the following factors:

- Composition of the coal feedstock and sorbents
- Combustion conditions
- Composition and mineralogy of the fly ash
- Relative amounts of fly ash, unreacted sorbent, and desulfurization products
- Reagent ratios

Chemical and Mineralogical Composition

FGD Material from Wet FGD Systems

Wet FGD systems frequently use calcium-based sorbents and produce either wet FGD material (unoxidized wet FGD material or sulfite-rich wet FGD material) or FGD gypsum (from forced-oxidation systems). These materials have similar bulk chemical compositions but have different mineralogical compositions. The chemical composition of wet FGD material depends largely on the sorbent used for desulfurization and the proportion of fly ash collected with the FGD residues. In most wet FGD systems, FGD residues are collected as a separate byproduct stream (Clarke, 1993). Since flue gas contains sulfur primarily as SO₂, the initial material formed is calcium sulfite (CaSO₃). To generate calcium sulfate, the material must be oxidized. This can be done in the scrubber system with a process called in situ forced oxidation. In this process, excess air is added to the system to oxidize the calcium sulfite to calcium sulfate as shown below:



If it is desired or advantageous to oxidize the FGD material as a slurry outside of the scrubber, this can be easily done by passing either oxygen or air through a slurry acidified to around pH 4.5. The pH adjustment is necessary as the oxidation proceeds through the bisulfite (Ca[HSO₃]₂). It is necessary to form the bisulfite through acidification because of the extremely low solubility of the calcium sulfite. Calcium bisulfite is much more soluble, and because the ex situ oxidation occurs in solution, the much higher solubility of the bisulfite increases the reaction rate.

Both wet FGD material and FGD gypsum are primarily crystalline in their morphology. FGD gypsum is composed of finely divided cube- or rod-shaped crystals ranging from 1–250 μm (Coal Research Establishment [CRE], 1992). The purity of FGD gypsum typically ranges from 96%–99% (Coclough and Carr, 1991). Wet sulfite-rich FGD material is composed primarily of calcium sulfite hemihydrate (hannebachite).

Table 1 lists the typical bulk chemical composition for wet FGD material from systems in which fly ash is removed before the scrubber. The chemical compositions of bituminous, subbituminous, and lignite fly ash are included for comparison purposes.

In some systems, fly ash is used as part of the sorbent. High-calcium fly ash can be used but has been reported to be more abrasive than limestone. When fly ash is used as part of the sorbent, the bulk chemistry and mineralogy of the FGD material will reflect the chemistry and mineralogy of the fly ash based on the percentage of fly ash used.

The major and trace element compositions of several samples of FGD gypsum from Germany, Japan, the United Kingdom, and the United States are listed in Table 2. Most of the major and trace elements leave the FGD system in the gypsum or wet sulfite-rich FGD material. Al, As, Ca, Fe, Pb, Sb, Si, and Ti are the elements mainly left in the gypsum. Between 10% and 40% of Al, As, Cr, Cu, F, Fe, Ni, Sb, Sc, Si, Sm, Ti, U, V, and W leave the plant in the wet

Table 1. Typical Chemical Composition of FGD Residues

	Wet Sulfite-rich FGD Material		FGD Gypsum	Fly Ash (bituminous)	Fly Ash (subbituminous)	Fly Ash (lignite)
SiO ₂	0.1–7.4	0.1–6.3		43–64	30–45	12–49
Al ₂ O ₃	0.1–6.0	0.1–5.1		11–32	17–21	6.3–16
Fe ₂ O ₃	0.1–6.0	0.1–5.7		3.5–25	3.9–6.5	3.7–14
CaO	38–52	27–32		0.7–20	17–30	16–34
MgO	1.3–6.1	1.0–4.9		0.6–1.6	3.4–6.4	3.8–11
Na ₂ O	0.1–0.9	0–0.6		0.2–4.0	0.2–8.4	0.6–6.1
K ₂ O	0–0.6	0–0.6		0.5–3.0	0.3–1.0	0.4–2.1
SO ₃ ²⁻	54–63	44–46		0.1–11	1.1–5.0	0.4–30
Typical Solids Content	5–10	5–10				

Sources: Smith, 1992; CARRC Database.

Table 2. Chemical Analysis of FGD Gypsum*

	A	B	C	D	E	F	G	H	I	J	K	L	M	Nat.
Trace Elements, ppm														
As	<1	1	1	1	1	1	1	1	1	2	1	1	1	<1
B	<5	<5	11	10	100	10	11	4	29	<5	21	11	24	9
Ba	12	9	7	6	6	<1	<1	<1	<100	13	<1	6400	200	4
Cd	<1	<1	<1	<1	<1	<1	<1	<1	<1	2	<1	<1	1	<1
Cr	4	5	10	3	4	4	4	6	4	5	9	24	3	1
Cu	64	9	12	3	5	3	<1	<1	5	7	<3	3	3	7
Hg	<3	<3	1	1	<1	<1	<1	<1	<1	<3	<1	<1	<1	<3
Mn	10	11	28	49	32	15	3	17	8	94	10	35	15	4
Mo	<1	<1	<1	<2	<1	<3	<3	<3	<2	<1	<3	<3	<2	<1
Ni	19	4	6	4	7	<3	<3	<3	5	17	<3	<3	3	2
Pb	1	2	7	3	<2	4	1	12	2	3	1	47	28	<1
Se	3	2	15	10	11	8	9	12	3	<1	4	6	<1	<1
V	8	16	12	12	12	10	10	10	10	21	12	10	10	27
Zn	10	8	3	<1	7	5	3	5	8	16	5	20	8	5

* A–I: Germany, J: Japan, K–L: USA, M: UK, Nat.: natural mineral gypsum sample.

Source: CRE, 1992.

sulfite-rich FGD material. The amounts of major, minor, and trace elements included with the FGD material are highly dependent on the amount of ash also included. If ash is excluded, the contribution of trace elements in the FGD material is limited to those that are air toxic constituents and are present in the flue gas either as extremely fine particulates or vapors. Some elements, especially the more volatile ones, are removed mainly in the wastewater (Meij, 1989). It is recognized that the mercury content of FGD materials is primarily determined by the species produced in the combustion system. Oxidized mercury, likely present as mercuric chloride, is highly retained in FGD systems, while elemental mercury mostly passes through the FGD

system. The Energy & Environmental Research Center (EERC) (Hassett and others, 1997) noted that some trace elements were present in measurable quantities in FGD gypsum produced in pilot-scale ex situ oxidation of wet FGD material. These elements were mercury, chromium, and chlorine (present as chloride), and although they were present in measurable amounts, it is important to note that the mercury and chromium were present at very low levels, with leachate concentrations less than the primary drinking water standard levels. Chloride was present at 110 ppm. Although it was known from previous analyses that trace elements were present in the wet FGD material, it was anticipated that the oxidation process used would facilitate the removal of contaminants. In follow-up work, solid materials, reaction waters, and leachate were all analyzed in an effort to determine the fate of these trace constituents relative to the FGD gypsum produced using the air oxidation process. During the oxidation of the wet FGD material, many of the trace elements partitioned to the liquid phase because of recrystallization purification as well as lowering of solution pH. Certain trace elements were present in measurable concentrations in the produced FGD gypsum, but in leaching experiments, only a small percentage of the total was released to the leachate. Mercury behaved differently than other trace elements in that it retained its association with the FGD throughout the oxidation process. It is not known what the mechanism of mercury association is, but despite the dissolution–oxidation–recrystallization process that the material undergoes, mercury is associated with both the pre- and post-oxidation material. The concentrations remaining are, for the most part, immobile under water leaching. Findings of trace element partitioning and fate in the ex situ oxidation of wet FGD material are summarized below.

- Potentially problematic trace elements, including heavy metals and chloride appear to partition into the liquid phase during the oxidation process, likely from recrystallization purification of the product as well as pH adjustment to the 4.5 necessary for air oxidation.
- Concentrations of many of the potentially problematic trace elements are not especially high.
- Mercury sorbed or otherwise captured in wet FGD systems may tend to remain associated with the solids if ex situ oxidation is used for the production of gypsum.
- Trace elements remaining in the scrubber sludge at measurable or potentially problematic levels have been found to be leached at concentrations at or below primary drinking water standards.
- The degree of dewatering that can be accomplished will account for concentrations of trace elements in the produced gypsum that are inversely proportional to the efficiency of dewatering. This is because of the partitioning of the trace elements into the liquid phase during the oxidation process.

Although the use of in situ forced oxidation appears to be a superior alternative for the production of gypsum without the bother of the additional solution chemistry required by an air oxidation system, the material produced in a forced-oxidation system will likely be of a lower overall purity with respect to total calcium sulfate content since unreacted calcium hydroxide

will be present in its original form and trace elements trapped in the scrubber material will remain there in original concentrations. These are favorably partitioned into the liquid phase during air oxidation, especially heavy metals.

FGD Material from Dry FGD Systems

Like wet FGD materials, the chemical composition of spray dryer material residues depends on the sorbent used for desulfurization and the proportion of fly ash collected with the FGD residues. Table 3 lists the major and trace element compositions of some spray dryer materials. Spray dryer FGD materials consist of fly ash entrained with reacted and unreacted

Table 3. Chemical Analysis of Spray Dry Scrubber Material

	A	B	C	D	E
Major Elements, wt%					
SiO ₂	7.9	10.6	8.7	47.1	32
Al ₂ O ₃	4.7	4.5	4.1	24.8	15.3
Fe ₂ O ₃	2.2	4.4	1.9	10.1	3.8
CaO	1.9	1.5	1.0	1.6	24.1
MgO	37.8	35.6	33.6	4.8	2.9
Na ₂ O	0.3	0.3	0.2	0.9	1.67
K ₂ O	0.4	0.6	0.3	2.6	0.52
CO ₂	17.0	20.1	10.6	—	
SO ₃ ²⁻	30.0	17.4	18.8	—	
SO ₄ ²⁻	10.5	7.0	24.6	1.2	
Cl ⁻	2.2	0.9	3.0	<0.1	
C (org.)	0.2	0.2	0.1	1.0	
Trace Elements, ppm					
As	5	11	10	110	
B	100	115	150	200	
Ba	465	270	4000	1500	
Cd	1	3	7	<3	
Cr	40	50	34	145	
Cu	47	43	46	230	
Hg	<1	<1	<1	1	
Mn	270	420	170	780	
Mo	3	5	<3	22	
Ni	32	36	35	170	
Pb	28	110	57	205	
Se	4	5	7	7	
V	60	65	70	280	
Zn	94	380	130	370	

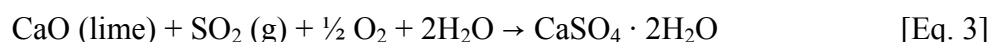
A–C: spray dry scrubber residues, D: bituminous fly ash, E: MN FGD.

A–D Source: CRE, 1992; E Source: Solem-Tishmack, 1993.

sorbent. The average particle size ranges from 20–40 μm . The fly ash in dry FGD materials has similar particle size, density, and morphology to those of conventional fly ashes, but FGD materials have lower bulk densities (Thompson and others, 1988). The difference in bulk density is due to variations in the chemical and mineralogical characteristics of the reacted and unreacted sorbent. Dry FGD materials contain higher concentrations of calcium and sulfur and lower concentrations of silicon, aluminum, and iron than fly ash. The principal reaction product of FGD is hannebachite (calcium sulfite hemihydrate) (Solem-Tishmack, 1993):



Under more oxidizing conditions, gypsum may also form:



Unused sorbent remains as portlandite (calcium hydroxide) in the residuals (Solem-Tishmack, 1993).

Dry FGD materials can vary widely in their properties depending on their source. Thompson and others (1988) collected dry FGD materials from different plants that used different types of boilers and burned different types of coal. They found the residuals had a moderate to wide range of variability in their chemical, physical, and mineralogical properties. The amount of unused sorbent (portlandite) varied the most by a factor of 14. This variation depended on whether or not the plant recycled its residuals.

Physical and Engineering Properties of FGD Material

FGD Material from Wet FGD Systems

The physical properties of wet FGD materials vary significantly depending on the relative proportions of sulfate and sulfite from each system (Clarke, 1993). The average bulk density of gypsum depends on the particle shape with approximately 1200 kg/m^3 for blocky crystals and roughly 600 kg/m^3 for needlelike crystals. Wet sulfite-rich FGD material historically was termed “scrubbing or FGD sludge” because of its thixotropic properties. The term “sludge” is less commonly used by the coal ash industry. Thixotropic properties enable it to stiffen in a relatively short time on standing but, upon agitation or manipulation, to change to a very soft consistency or to a fluid of high viscosity; the hardening process is completely reversible. Wet sulfite-rich FGD material is difficult to dewater; however, its physical properties can be modified by “fixation” or “stabilization” with fly ash, portland cement, or other additives.

FGD Material from Dry FGD Systems

The overall physical and handling properties of the residues from most spray dryer materials are similar to fly ash. The bulk density of spray dry system residues, with only a small proportion of ash, is about 600 kg/m^3 compared to 1000 kg/m^3 for fly ash (Jons, 1987; CRE,

1992). Particle-size distributions of these materials indicate that most materials can be classified as silt-size range. The bulk density of residues from spray dryer FGD systems varies from 780 to 1250 kg/m³ (Perri and others, 1988). An example of an x-ray diffraction of spray dryer material can be found in Figure 2 (Weber and others, 1993). The hannebachite is the sulfite.

FGD AS A MULTIPOLLUTANT CONTROL TECHNOLOGY

Background on Mercury Emission

The operation of coal-fired power plants results in the generation of CCBs that already contain mercury; however, that mercury is presumably bound mercury that is relatively insoluble and nonleachable (EPA, 2002). The type of mercury that is of greatest concern is mercury emitted into the air. Although mercury is emitted from coal-fired power plants in very low concentrations, as a group, coal-fired boilers represent the largest unregulated source of mercury emissions to the environment, accounting for about one-third of the total anthropogenic emissions (EPA, 1997). Further assessment based on EPA's 1999 Information Collection Request (ICR) indicates that approximately 40% of the 75 tons of mercury contained in the coal burned in the United States is captured in ash and scrubber residues and 60% is emitted to the atmosphere (Kilgroe, 2000; Chu and others, 2000). In 1999, EPA estimated that the electric utility industry emitted 43 tons of mercury from 1149 units at 464 coal-fired power plants through both air and solid emissions. Projections for 2010 without regulations include approximately 60 tons of emission from 1026 units at 426 coal-fired plants (Duclos, 2001).

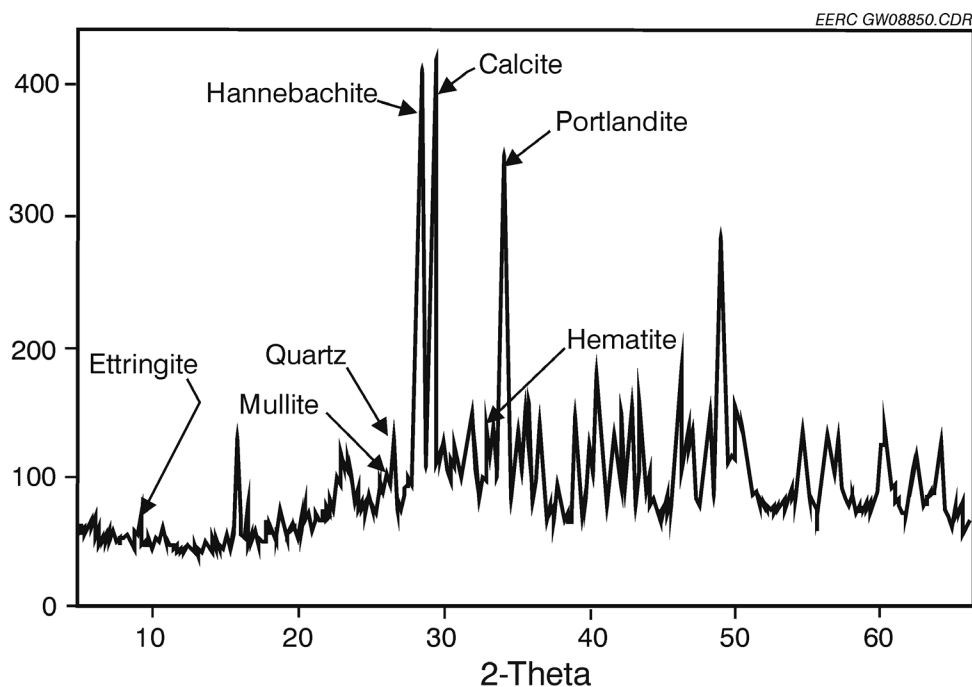


Figure 2. Diffraction of spray dryer material.

Increased control of mercury emissions from coal-fired power plants may change the amount and composition of CCBs. Such changes may increase the potential for release of mercury to the environment from either landfilling or utilization. Mercury volatilization from CCBs in landfills and/or surface impoundments is expected to be low because of the low temperatures and relatively small surface area involved. For mercury control technologies using dry or wet FGD scrubbers, the byproducts are typically alkaline and the acid leaching potential of mercury from these byproducts is expected to be minimal (EPA, 2002a). EPA (2002b) predicts that future policy for mercury control will designate activated carbon injection downstream of the combustion process.

Background on Regulations

As previously mentioned, there are no specific regulations for mercury for electric utilities. The CAAA of 1990 did require EPA to regulate hazardous air pollutants (HAPs) using a maximum achievable control technology approach, commonly referred to as a MACT approach. MACT standards were put in place for any sources that emitted 10 tons or more of a particular pollutant. Utilities, on the other hand, were a source category to be treated separately. EPA was required under the CAAA to perform further studies on HAPS for electric utilities. The two reports that came out of this directive were the Mercury Report to Congress and the Utility Report to Congress. Based on the conclusions of these reports, EPA determined it necessary to regulate mercury emitted from electric utilities. Thus, there were no immediate or direct regulations for mercury and utilities, but the process indirectly led to mercury regulations for this particular source category. The form of regulation is still being debated (Pavlish, 2002). However, EPA has developed a five-pronged approach to controlling mercury emissions from power plants (EPA, 1998):

- Increasing public access to information concerning mercury emissions from power plants
- Seeking to reduce risk to highly exposed populations through public information
- Making maximum use of the reductions in mercury emissions that can be achieved from controlling other pollutants
- Encouraging the development of mercury emissions monitoring and control technologies
- Further research to increase understanding of the nature and fate of mercury emissions from power plants so as to form a basis for future controls

Most recently, on February 14, 2002, President Bush announced his administration's initiative to address concerns about power plant emissions. The Clear Skies Initiative (CSI) cuts (by 70%) power plant emissions of the three major air pollutants: nitrogen oxides, sulfur dioxide, and mercury. NO_x emissions will be cut by 67%, from current emissions of 5 million tons to a cap of 2.1 million tons in 2008 and 1.7 million tons in 2018. SO₂ emissions will be cut by 73%, from current emission of 11 million tons to a cap of 4.5 million tons in 2010 and 3 million tons

in 2018. The Bush administration anticipates that the national cap on mercury emissions will cut emissions by 69% from current emissions of 48 tons to a cap of 26 tons in 2010 and 15 tons in 2018. To accomplish these cuts, the CSI uses a market-based approach which will "... cut pollution further, faster, cheaper, and with more certainty, using a 'cap-and trade' program, replacing a cycle of endless litigation with rapid and certain improvements in air quality... Saves as much as \$1 billion annually in compliance costs that are passed along to American consumers, improves air quality, and protect the reliability and affordability of electricity. Use the model of our most successful clean air law—the 1990 Clean Air Act's acid rain program—and encourage the use of new and cleaner pollution control technologies" (Palmisano and Burnett, 2002). It should be noted that this plan has been fiercely scrutinized because it does not, in many people's view, reduce emissions enough, starts too late and, therefore, has a lower monetized benefit.

Further regulations are scheduled to be proposed in late 2003 and should be final by late 2004, with a compliance date of late 2007. These regulations will affect all new and existing units. EPA has not yet determined the level of control that will be required. However, there are at least five bills pending in the 107th Congress that would require regulation of mercury emissions from coal- and oil-fired utility boilers. Based on EPA's extensive ICR test program, it is expected that dry FGD systems on boilers firing bituminous coal and wet FGD systems preceded by fabric filters on boilers firing bituminous coal are likely to be able to meet the predicted 90% control requirement by the end of the decade (Weilert and others, 2002).

In addition to federal regulations, states have begun developing their own emission control regulations and, in some cases, identified specific control efficiency requirements. These states are as follows:

- Connecticut
- Maine
- Massachusetts
- Minnesota
- New Hampshire
- New Jersey
- Wisconsin

The Connecticut Department of Environmental Protection (2002) anticipates a reduction of 8900 tons of SO₂ emissions after 2003 in addition to a reduction of baseline NO_x emission by 30%, or 3483 tons, per year. Massachusetts has adopted regulations that reject the use of "averaging," meaning companies owning more than one plant cannot have a high-polluting facility just because they operate a clean plant in another part of the state. Massachusetts regulations apply to NO_x, SO₂, and CO₂ emissions, and a mercury standard is expected to be proposed in 2006 (Commonwealth of Massachusetts, 2001). According to Weilert and others (2002), New Hampshire has proposed a 50% reduction in emissions from electric utility boilers by 2003 and 75% by 2005. Wisconsin has proposed a phase-in of mercury reductions over the next 15 years, beginning with 30% reduction by 2006 and extending to 50% reduction by 2011 and 90% by 2016 for utility boilers only (Weilert and others, 2002).

Control Technologies

Currently, U.S. utilities make use of various technologies to reduce mercury emissions; however, these technologies are not specifically designed to reduce mercury emissions (EPA, 2002). Technologies that are used to reduce particulate matter, SO₂, and NO_x also reduce mercury emissions with varying levels of effectiveness (EPA, 2002). Some of these technologies involve the installation of specialized equipment, while others rely on modification of operating procedures or the use of specific fuels. Because of the large number of U.S. fossil-fueled facilities and the various regulatory requirements, there is a tremendous variety of emission control equipment provided and installed by many different suppliers and vendors (EEI, 1993).

Because the chemical species of mercury emitted from coal-fired power plants vary from plant to plant, no single control technology removes all forms of mercury. There remains a wide variation in the end costs of control measures for utilities and the possible impact of such costs on utilities. Preliminary estimates of national control costs for utility boilers (based on pilot-scale data) are in the billions of dollars per year (EPA, 1997).

As new mercury control regulations are adopted, more innovative technologies are being studied to address mercury extraction and removal from coal-fired flue gas. With more than 200 of the largest coal-fired power plants in the United States utilizing FGD systems, these systems still remain the most popular method of mercury removal. Although these systems were designed primarily to remove SO₂, wet scrubbers also entrain oxidized mercury in the scrubber water that can reach 600 ppb (Duclos, 2001). FGD systems have not been shown to remove reduced mercury, and since the mercury species emitted varies by coal, FGD systems will not provide mercury reductions for some coals.

To optimize mercury removal using FGD, investigations have been initiated to oxidize mercury from the elemental form (Hg⁰) to the oxidation form (Hg⁺²) so it can be removed in existing FGD systems. One example of this research was reported by Babcock & Wilcox and McDermott Technology, Inc., at the March 19, 2002, National Energy Technology Laboratory (NETL) Mercury Workshop and is noted on the DOE NETL Web site (DOE NETL, 2002).

New fine particulate control technologies, such as the EERC's ADVANCED HYBRID™ technology (Miller and others, 2002), may also offer enhanced mercury control. The EERC is currently evaluating the ADVANCED HYBRID™ technology for mercury capture under funding from DOE NETL.

Human Risk

Much is still unknown about the relationship of power plant emissions and mercury concentrations in humans. Concentrations of mercury in air are usually low and of little direct concern; however, atmospheric mercury contributes to the mercury loading in surface waters where it can bioaccumulate in fish and animal tissue in the form of, methylmercury (EPA, 1998).

The most direct threat of mercury exposure to humans occurs by eating contaminated fish. Exposure to high levels of mercury has been associated with serious neurological and developmental effects in humans. The effects can include subtle losses of sensory or cognitive ability, tremors, inability to walk, convulsions, and death. Because a developing fetus may be the most sensitive to the effects from methylmercury, women of child-bearing age are regarded as the population of greatest interest (EPA, 1998).

HANDLING OF FGD MATERIAL

Because many utilities in the United States dispose of wet sulfite-rich FGD material in ponds or lagoons, pipeline transportation is most effective (Moore, 1992). A moisture content of <10% is desired for transport because moisture contents of 12%–15% can make the material sticky and clog up systems, and a moisture content of <5% can create dust (Clarke, 1993). Wet sulfite-rich FGD material is sometimes stabilized or fixated by addition of fly ash, cement, or other additives. The stabilized material is easier to handle and transport because the stabilization result reduces or eliminates the thixotropic properties of the materials. Stabilized wet sulfite-rich FGD material has been used for liners and feedlot surfaces (Butalia and others, 1999).

Wet sulfite-rich FGD material may be dewatered through filtering. This filtered material may be referred to as filter cake. After disposal in wet conditions, such as lagoons or ponds, FGD material may be dewatered by “dry-stacking” which allows excess water to naturally migrate from the FGD material.

Handling FGD gypsum can be difficult because the material is abrasive, sticky, compressible, and considerably finer (<0.2 mm) than natural gypsum (CRE, 1992). Because of the difference in mixed natural gypsum and FGD gypsum, only limited quantities of FGD gypsum could be used to replace or supplement natural gypsum in older gypsum wallboard factories. New gypsum wallboard plants have been designed to accommodate the finer FGD gypsum.

The bulk physical properties of dry FGD materials are similar to fly ash; therefore, they must be handled similarly. While the bulk appearance and properties may be similar to fly ash, dry FGD material is primarily crystalline in its morphology, and fly ash is primarily glassy or amorphous. As a result, flow characteristics of dry FGD material may vary significantly from fly ash. Some powders may require conditioning to transport. The typical moisture content of the conditioned residues is about 10%. The majority of dry FGD materials can be transported by rail, road, water, or pipeline (Clarke, 1993); however, it is suggested that residues discharged directly from the spray dryer FGD unit are best transferred using mechanical conveyors (Klimek and others, 1987).

Materials discharged directly from the spray dryer FGD system are best transferred using mechanical conveyors and may be transferred using a pneumatic system. These materials may require conditioning prior to transport to minimize dusting. The typical moisture content of these materials is 10%. Conditioning with water aids compaction of residues and may display thixotropic properties (CRE, 1992).

FGD MATERIAL UTILIZATION

Record levels of construction activity in North America and the recovery of most Asian economies triggered significant expansion in the gypsum industry during 1999 (The Roskill Consulting Group, 2000); however, the U.S. gypsum industry experienced a decline in both production and consumption in 2000 (Olson, 2000). Bruce (2002a) suggests the U.S. decline could be attributed in part to the globalization of the industry. It is important to note that although the overall gypsum industry experienced a downturn in 2000, the production and consumption of synthetic gypsum increased largely because of the construction of wallboard plants specifically designed to use the material as a feedstock.

The primary source of synthetic gypsum is from forced oxidized FGD systems. Synthetic gypsum is becoming a very viable material and has gained widespread acceptance as a raw material in the production of gypsum wallboard and cement. These two markets account for in excess of 80% of all natural gypsum and virtually all synthetic gypsum consumption in North America.

During the next several years, the use of mined gypsum may decline significantly in the United States as greater quantities of synthetic gypsum are produced. The U.S. FGD market is expected to grow by 5000 MW annually over the next 7–8 years as a consequence of the newly introduced legislation (Global Gypsum, 2002). This large increase in production has made it possible for other companies to move into the market and for existing companies to expand into regions that were previously untapped. It is important to note that although more power plants are producing FGD gypsum, there are also increasingly frequent reports of shortages. Today, synthetic gypsum represents about 18% of the gypsum used in the United States (Bruce, 2002a), and some forecasts predict this percentage will increase to 30% by 2005 (Global Gypsum, 2001).

FGD gypsum is primarily produced in North America, Europe, and Japan; however, output is spreading to less developed countries where it will become an increasingly important source of material in the future (The Roskill Consulting Group, 2000). Based on the ACAA Coal Combustion Product Production and Use Statement, 25,652,994 tons of FGD material was produced in the United States in 2000, and 4,824,727 tons (nearly 19%) was utilized. As illustrated in Table 4, synthetic gypsum accounted for more than 15% of the total domestic gypsum supply in 2001. Synthetic gypsum includes FGD gypsum from coal-fired power plants and by-product gypsum from other sources.

Table 4. Gypsum in the United States, million tons

	1997	1998	1999	2000	2001
Crude	18.6	19.0	22.4	19.5	18.8
Synthetic ^a	2.7	3.0	5.2	5.2	6.1
Calcined ^b	17.2	19.4	23.3	2.1	17.7

^a Data refer to amount sold or used, not produced.

^b From domestic crude.

Source: U.S. Geological Survey (USGS) (2002).

FGD materials have been successfully utilized in a wide variety of applications. According to the USGS (2002), 95% of the gypsum consumed in the United States is used for wallboard products, building plasters, and the manufacture of portland cement. The USGS overall utilization rate (2002) is comparable to ACAA (2001) statistics illustrated in Figure 3. It is important to note that ACAA's data do not indicate if the FGD materials used are wet FGD material, FGD gypsum, or dry FGD materials; however, it is reasonable to assume that wet FGD material is generally stabilized prior to use. The thixotropy of wet FGD material limits its usefulness.

FGD materials have the potential to be beneficially reused in numerous applications if the economics are in place. It is reasonable to assume that FGD gypsum is the primary FGD material represented by the use figures. Only gypsum can be used in wallboard and cement. FGD gypsum and sulfite-rich FGD materials would likely be used preferentially in agricultural applications.

Although FGD materials have the potential to be used in a variety of applications, many of those applications never reach the commercial phase for a number of reasons, including economics and government regulations. The following nonexhaustive list of current commercial utilization practices for FGD materials was derived from a variety of sources, including symposium proceedings, Internet searches, and conversations with experts in the industry:

- Wallboard (regular, Type X, sheathing, soffit board, water-resistant gypsum, backing board, lath, veneer base, coreboard, gypsum liner board, predecorated, foil backed, board for manufactured housing, wood chip boards)

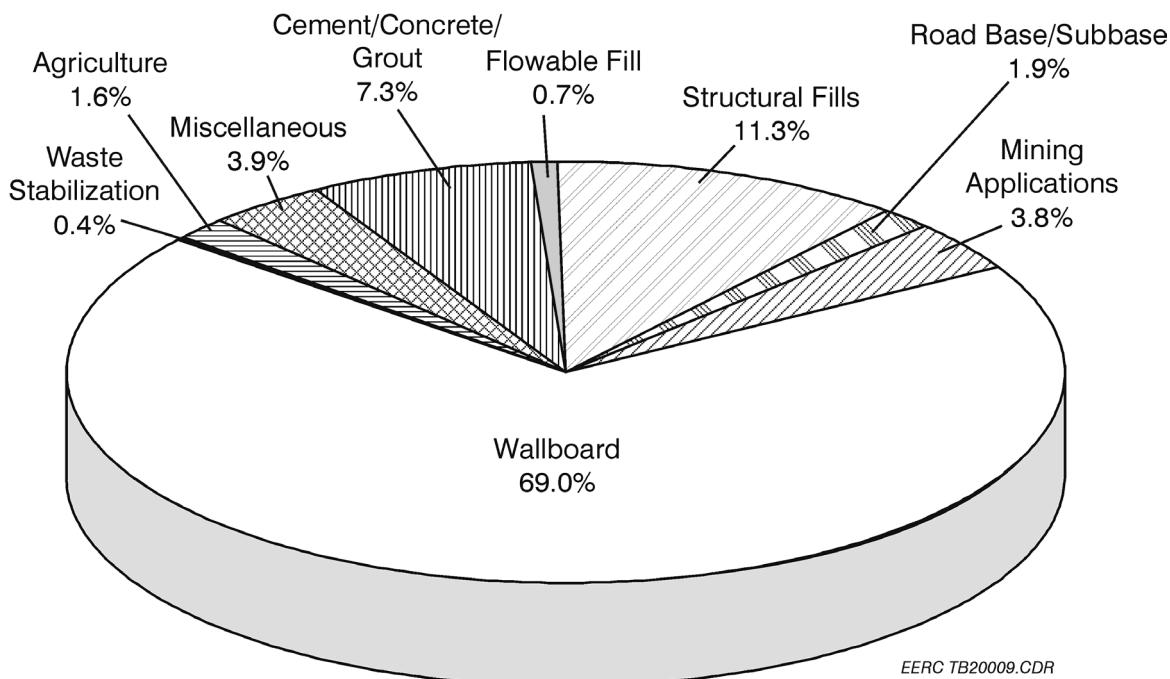


Figure 3. FGD material utilization applications.

- Structural fills
- Mining applications
 - Neutralization or encapsulation of acid-producing materials
 - Barrier to acid mine drainage formation/transport
 - Alkaline amendment to neutralize acid-producing rock
 - Subsidence control in underground mines
 - Filling underground mine voids to control acid drainage
 - Pit filling to reach approximate original contour in surface mines
 - Soil amendment
 - Synthetic soil component
- Portland cement (Primarily used as a grinding aid and set retarder)
- Plaster
- Agriculture
 - Acid soil neutralization clay breakdown and as a calcium and sulfur source
 - Sodic soil reclamation
 - Carbon sinks in forestry
 - Feedlot surface stabilization
 - Crop storage pads
- Floor underlayment
- Glass making
- Pigments and/or fillers in paper, plastic, food, pharmaceutical, fertilizer, pesticide, and herbicide

Products developed and based mainly on a-hemihydrate including the following:

- Self-leveling floor screeds of varying strengths (very common in Europe, particularly Germany, for heat and sound insulation)
- Double floor systems as cavity floor and raised access floor (“computer floor”)
- Mining mortars (consolidation, embankment, rock stabilizers)
- Tunnel mortars
- Construction products (adhesives, thin-layer systems, toppings)
- Molding plasters

Magnesium hydroxide markets include the following:

- Acid neutralization
- Fuel additives
- Feedstock for refractories, magnesium metal, and the chemical industry

Pyrite coal spoil and gypsum sludge can result in valuable products, namely, sponge iron and lime.

Table 5 lists the potential uses of FGD gypsum and dry FGD material. It is important to note that some applications listed are not commercially available at this time.

Table 5. Potential Uses of Dry FGD Material

High Potential	Moderate Potential	Low Potential
Structural Fill	Cement production	Gypsum/wallboard
Grout/Mine Backfill	Cement replacement	Metals extraction
Stabilized Road Base	Soil stabilization	
Synthetic Aggregate	Sludge stabilization	
Lightweight Aggregate	Mineral filler	
Mineral Wool	Agricultural use	
Brick Production	Ceramic products	
	Liner material	

ECONOMIC ISSUES ASSOCIATED WITH FGD UTILIZATION

According to the Combustion 2000 Project (2001), the technical challenges of producing commercially usable by-product gypsum have mostly been solved, and the operating changes required to use these materials in commercial applications are becoming relatively well established. The area that remains a significant challenge is structuring successful relationships between producers and consumers. Ultimately, economic issues are the driving force that will determine the level of utilization. However, a by-product that is less expensive than a raw material will not automatically be sought after for industrial use. The factors which govern its desirability as a product are much more diverse.

Product constancy and reliability are the primary factors associated with the use of synthetic gypsum. Synthetic gypsum must consistently meet stringent quality parameters to be utilized in wallboard and other manufacturing. Two main areas that have received attention as process improvements are additives and forced oxidation. Additives are employed to improve SO₂ removal by increasing the liquid-phase alkalinity. Forced oxidation of sulfite to sulfate (eliminating major dewatering problems) is an important major improvement in wet FGD systems. This has led to the development of the production of commercial-grade FGD gypsum (Combustion 2000 Project, 2001). Parameters that are most important to product quality include free moisture, purity, soluble salts, pH, particle size, and surface area. The free or surface moisture of synthetic gypsum usually ranges from 6% to 25%. Assuming the synthetic gypsum

meets particle-size requirements and does not contain any harmful impurities, a higher-purity synthetic gypsum will allow a lower-weight board to be produced without sacrificing strength (Henkels and Gaynor, 1997). Soluble salt impurities are common in natural and synthetic gypsums. The four soluble salt ions typically tested for are magnesium, potassium, sodium, and chloride. Chloride is the most common contaminant in FGD gypsum. Soluble salts found in FGD gypsum can often be washed away.

Because the gypsum industry tends to have a much more exaggerated cycle than other industries within the construction industry, the commitment of the gypsum supplier is critically important to encourage a partnership with consumers. Commitment is seen in numerous forms, including supply reliability because building materials production plants operate very consistently, thus making supply interruptions difficult to manage; product quality to ensure impurities are controlled to acceptable levels; desirability of the local market region; and competitive advantage over competing materials.

Supply trends are essential to gypsum economics. Bruce (2002b), suggests that the biggest reason for the recent drop in the price for regular gypsum board has been the huge increase in capacity that has been put in place over the last four years. Bruce also suggests in a more recent article (2002a) that the industry has experienced shortages of synthetic gypsum. These shortages could be a result of the industries' peak periods, where an excess capacity is needed to keep up with surges in demand. Despite the increase in wallboard production, some regions in the United States still remain in short supply and other regions have a severe surplus.

A critical element in the economic consideration of gypsum markets, natural or synthetic, is transportation costs. Gypsum wallboard, which is made from gypsum, and cement of which gypsum is a component, are bulk items sensitive to handling and transportation costs. For this reason, location of the gypsum source and manufacturing plant, distance between the two facilities, and mode of transport are critical. Two separate sources of information have been quoted as identifying completely different methods of transportation as most practical. One source stated that rail is by far the most economical alternative for transporting high volumes of a coal by-product from the plant site to an industrial location. A second source stated that any transportation distance under 100 miles is commonly and most ideally performed by truck. This would allude to the fact that each method of transportation is site-specific and entirely dependent upon the type of by-product produced and the form of utilization intended for that by-product. Cement plants have traditionally been located on or adjacent to limestone or dolomite deposits and are usually located within 100 to 150 miles of their markets. Wallboard plants located in the United States are generally within the vicinity of major urban areas. For the most part, the natural gypsum for these industries comes from those mined closest to their plants. For several gypsum operations, the economics have been such that wallboard plants are located on or adjacent to the mine (Combustion 2000 Project, 2001); however this scenario has changed with the new mega-plants that are located near the synthetic gypsum suppliers (Miller, 2002).

DISPOSAL PRACTICES AND REQUIREMENTS

Currently, EPA classifies FGD material as a solid waste under RCRA Subtitle D. This classification places the responsibility to regulate disposal of FGD material on individual states. In the United States, regulations concerning selecting a disposal site and construction and operation of containment areas vary significantly between states. Collins (1992) lists the following parameters that generally play a role in development of state regulations:

- Sufficient distance above local groundwater table
- Soil conditions not prone to settling
- Siting away from limestone quarries, waterways, floodplains, wellheads, aquifers, or underground mines
- Suitable topography

For the utility, it is also important to consider the proximity of the disposal site to the power plant. Transportation costs can be significant, and utilities generally desire to minimize disposal costs.

The following disposal options have been used for wet FGD material (Smith, 1992):

- Hydraulically conveyed and ponded
- Dewatered and stacked
- Interbedded with fly ash
- Stabilized with lime, cement, and/or fly ash

Most U.S. utilities dispose of FGD material using ponding or lagooning techniques. Appendix B provides an illustration of FGD disposal practices by state. Wet FGD material is frequently thixotropic, which is the property of a material that enables it to stiffen in a relatively short time on standing, but upon agitation or manipulation, to change to a very soft consistency or to a fluid of high viscosity, the process being completely reversible.

FGD material disposal is likely to be impacted by rules for utility landfills/surface impoundments that are currently being developed by the EPA Office of Solid Waste. The final rule is scheduled for completion in March 2004. Discussions with industry representatives indicate some concern that the EPA rule for utility landfills/surface impoundments will require the phasing out of wet disposal sites. Wet FGD material would then need to be dewatered or stabilized prior to final disposal.

FUTURE FGD SYSTEM INSTALLATIONS AND FGD MATERIAL MANAGEMENT

The evolution of the electric power industry toward more competition has led utilities to delay capital expenditures for pollution control equipment as long as possible. Phase I of the

CAAA affected only 10% of the coal-burning electric utilities (Kalyoncu, 1997). Although FGD installations have not been as popular as originally planned, FGD technology has made considerable progress in SO₂ removal efficiency, reliability, and capital and operating costs during the past decade. Still, to meet stronger emission limits under Phase II of the CAAA, many utilities are expected to continue the cost-effective strategy of fuel switching. In a 1997 document discussing the impacts of the CAAA on electric utilities, DOE estimated that only 12 to 20 gigawatts of capacity would be scrubbed to comply with Phase II of the CAAA. The estimate was based, in part, on the fact that a number of utilities that had originally planned to install FGD systems had either deferred installation or canceled them in favor of fuel switching or purchasing allowances. The Bush Administration's CSI, announced early in 2002, provides a basis for an alternate prediction. The CSI requires significant additional reduction of NO_x and SO₂ emissions and the first-ever national cap on mercury emissions. It has been predicted that the number of FGD systems is expected to double in the next 7 years in response to emission regulations (Government Panel, 2001). Wet FGD control of SO₂ has the added advantage of removing oxidized mercury from the flue gas, so for some power plants, installation of wet FGD will provide multipollutant control to meet CSI SO₂ and mercury emission caps. The use of wet FGD for this type of multipollutant emission control will depend on the mercury species currently produced at a given power plant and future coal sources because the mercury species in the emissions are coal-specific. The extent of applicability of mercury removal technologies appropriated with FGD systems will depend on the nature and level of control dictated by mercury emissions regulations. Based on current information on mercury emission control technologies, FGD systems are attractive for several reasons: 1) control of both SO₂ and mercury, 2) demonstrated reliability, and 3) relative cost-effectiveness. The disadvantages include 1) the generation of high volumes of FGD material for management, possibly requiring disposal; 2) concern for mercury release from the FGD material under management scenarios; and 3) the specificity for control of oxidized mercury. These issues will need to be evaluated by individual companies considering the use of FGD for either SO₂ emission control or SO₂/mercury emission control.

Installation of FGD systems on currently nonscrubbed units will result in a large volume of FGD material for management. If predictions noted above are correct, the volume of FGD material could increase to 50+ million tons annually. If all new FGD systems were wet systems designed to produce FGD gypsum, the 25+ million tons of FGD gypsum produced would likely meet or exceed U.S. demand for gypsum, based on current gypsum production figures (USGS, 2002). U.S. gypsum wallboard manufacturers, cement manufacturers, and other industry/uses currently use nearly 20% of the FGD material produced in the United States (Figure 3). While these use applications have the potential to utilize much greater volumes of FGD gypsum, barriers to these uses will need to be addressed. These barriers include the competition with mined gypsum, quality issues, potential transportation issues, and others reported to the barriers to utilization of coal combustion/desulfurization by-products (Pflughoeft-Hassett and others, 1999). One area of potential increased use of FGD gypsum is in agricultural applications. FGD gypsum is currently used as an agricultural soil amendment (Figure 3), but before FGD gypsum from SO₂/mercury emission control will be readily accepted in agricultural applications, the issue of potential for mercury release from this FGD gypsum needs to be investigated. In the assessment of management options for multipollutant control FGD material/gypsum, the fate of the mercury needs to be considered.

As utilities consider options for SO₂ emission control for future installations, it will be important to follow the current EPA activities related to guidelines for CCB disposal and mine placement. These guidelines will impact the cost of new CCB disposal facilities which will be required if the predicted volumes of FGD material are produced and may impact the potential for FGD material to be placed in mine settings, a potential high-volume application for FGD material and other CCBs.

SUMMARY

FGD technology is well established and can be used to achieve the SO₂ emission reductions required in the CSI. Additionally, much work has been and continues to be done on the utilization of FGD materials. The use of FGD gypsum in place of natural gypsum in wallboard manufacture, cement production, and other existing products has been demonstrated and commercialized. This has been accomplished because most of the technical challenges of producing commercially viable FGD gypsum have been solved, and the operating changes required to use these materials in commercial applications are becoming relatively well established. An area that remains a significant challenge in increasing the utilization of FGD gypsum is structuring successful relationships between producers and consumers. Other FGD materials are still in the process of being investigated for use in various applications, and technical challenges may require further investigation and demonstration in order to lead to commercialization. The issue of mercury associated with FGD material and its potential release to the environment is part of investigations funded by EPA, DOE, and industry; results of these studies may impact management of FGD material in the future.

Federal regulations are currently driving future emission control for coal-fired power plants, but based on the information currently available, it seems apparent that additional FGD systems will be installed on existing power plants. The increased production of FGD material will make it increasingly important to optimize utilization. As was recommended in the 1993 EERC Report to DOE on the Barriers to Utilization of Coal Combustion/Desulfurization By-Products by Government and Commercial Sectors (Sondreal and others, 1993), procurement guidelines should be implemented at the federal level to encourage the use of CCBs, including FGD material. The CCB industry needs to be vigilant in following government actions in order to identify and take advantage of opportunities to effectively maintain or perhaps increase the current FGD material utilization rate of 20%. All levels of government and industry need to work together in order to achieve optimum utilization of CCBs, including FGD material.

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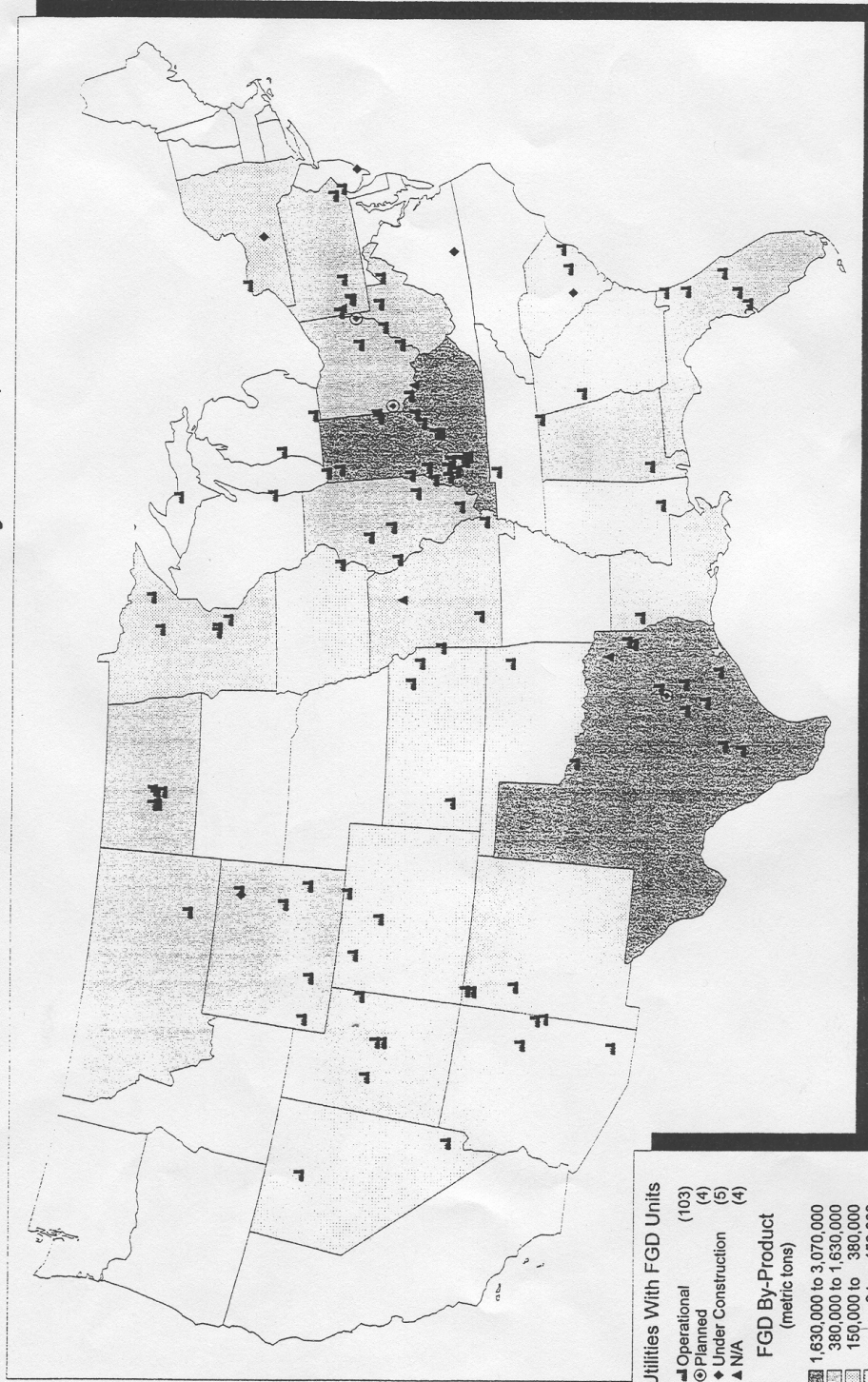
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APPENDIX A

FGD BY-PRODUCT GENERATED BY STATE, 1994

FGD By-Product Generated by State, 1994



Utilities With FGD Units

- ▲ Operational (103)
- Planned (4)
- ◆ Under Construction (5)
- ▲ N/A (4)

FGD By-Product

(metric tons)

- 1,630,000 to 3,070,000
- 380,000 to 1,630,000
- 150,000 to 380,000
- 0 to 150,000

FGD by-product generated in 1994 = 13,730,257 metric tons
 Top 10 states: TX=3,066,000; KY=1,916,000; IN=1,630,000; PA=1,174,000;
 OH=813,000; FL=685,000; MT=607,000; WV=458,000; AL=447,000; ND=419,000.

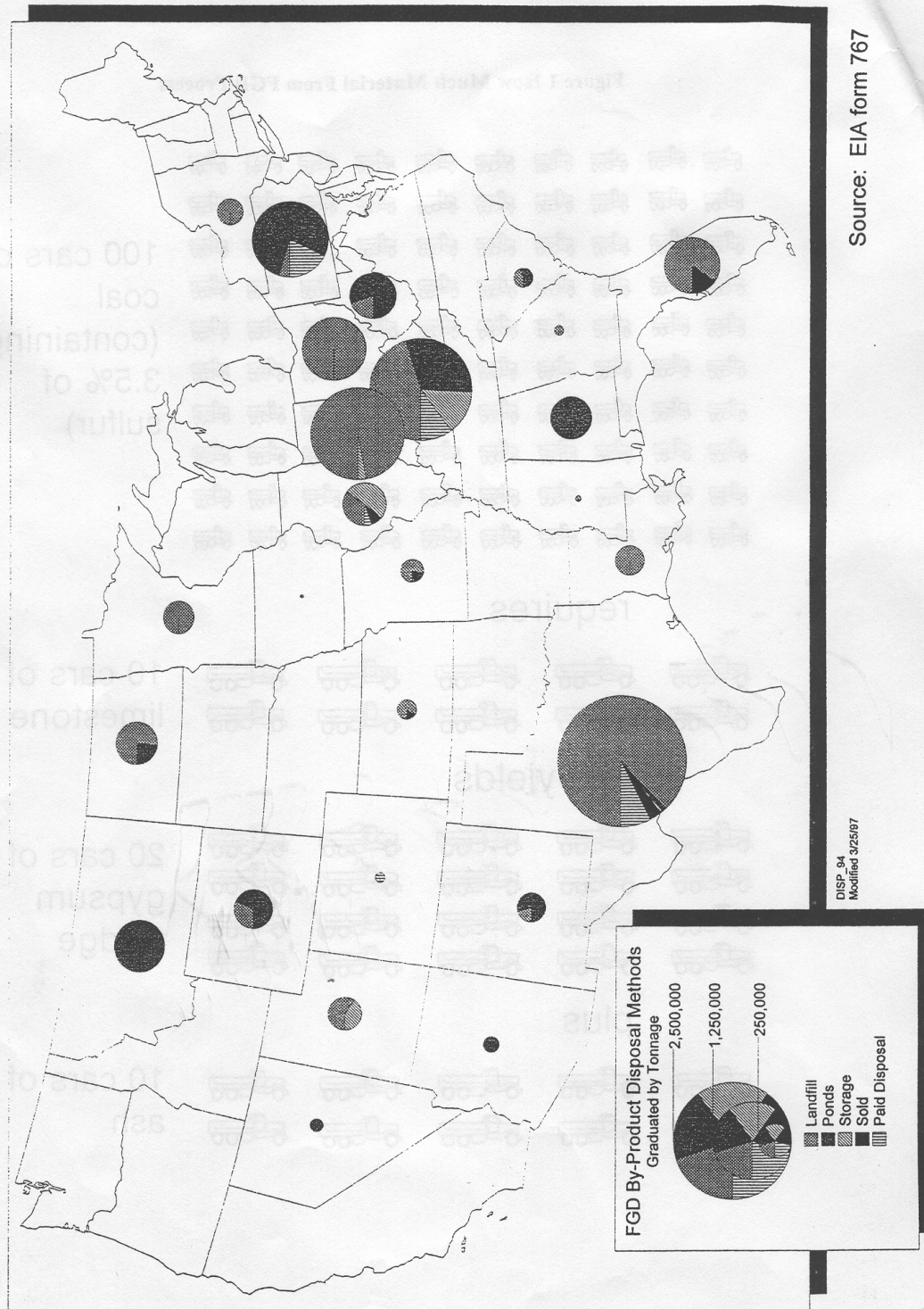
Source: EIA form 767

FGD-ST04
 Modified 3/31/97

APPENDIX B

STATE TOTAL FGD BY-PRODUCT BY METHOD OF DISPOSAL, 1994

State Total FGD By-Product by Method of Disposal, 1994



APPENDIX C
FGD SYSTEMS AND MATERIALS – DEFINITIONS

FGD SYSTEMS AND MATERIALS – DEFINITIONS

ACAA prepared the following definitions of FGD materials based on American Society for Testing and Materials (ASTM) terminology. This list was taken from a draft document dated July 10, 2001, and ASTM has not formally adopted all changes to these definitions.

Dry FGD – an FGD system in which calcium- or sodium-based sorbents, usually hydrated lime, are introduced to the flue gas. Dry FGD systems use less water than wet systems, usually remove fly ash and sulfur dioxide simultaneously, and generate a dry by-product. Spray dryer systems are the most common design. In a spray dryer, slaked lime slurry is sprayed into the flue gas, and the resulting by-product, dried by the heat of the flue gas, is collected in a particulate control device with the fly ash. Other dry systems inject dry sodium sorbent directly into the boiler exhaust duct. The by-product of a dry FGD system is referred to by various names that include dry FGD ash, dry FGD material, and dry scrubber material.

Dry FGD material – the product that is produced from dry FGD systems and consists primarily of calcium sulfite, fly ash, portlandite ($\text{Ca}[\text{OH}]_2$), and/or calcite. Lime-based sorbent system dry FGD material mainly consists of calcium sulfite and dry fly ash, along with minor quantities of calcium sulfate. Sodium-based sorbent systems mainly consist of sodium sulfite and dry fly ash along with minor quantities of sodium sulfate. Dry FGD material is being used in construction, engineering, and agricultural applications; however, most of the material is stored in landfills.

Dry sodium injection – see **dry FGD**.

Ex situ oxidation (wet FGD) – forced oxidation that occurs outside of the scrubber and is used to produce FGD gypsum.

FGD by-products – the term for the by-products from wet and dry FGD systems. See **wet** and **dry FGD material**.

FGD gypsum – gypsum formed from an oxidizing and calcium-based FGD process. Also, a precipitated gypsum formed through the neutralization of sulfurous acid (H_2SO_3) in FGD processes at coal-fired power plants. This gypsum can vary in purity, which is defined as the percentage of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, and generally is over 94% for use in wallboard manufacturing. The less pure gypsum can be stockpiled (gypsum stacking), placed in ponds or captive landfills, or utilized in agriculture or construction. The nearly pure or pure FGD gypsum is utilized beneficially. The pure FGD gypsum is manufactured to meet the specifications of wallboard-manufacturing companies and is used for wallboard manufacturing, for cement production, and as plasters. Large quantities of FGD gypsum are produced and utilized.

FGD material – a product of an FGD process typically using a high-calcium sorbent such as lime or limestone. Sodium-based sorbent and high-calcium coal fly ashes are also used in some systems. The physical nature of these materials varies from a wet thixotropic

sludge to a dry powdered material, depending on the process. The wet thixotropic sludge is usually from a lime-based reagent wet scrubbing process and is predominantly calcium sulfite. It is the end product of dewatering equipment such as vacuum filters or centrifuges, although it can be the end product of a sedimentation pond. This dewatered end product is usually stabilized by mixing with lime and fly ash or other materials for disposal in landfills. There are systems where the end product is not dewatered but is highly concentrated in solids as the underflow from a thickener. It is then mixed with fly ash and another material and pumped to a surface impoundment for disposal. The wet product from limestone-based reagent wet scrubbing processes is predominantly calcium sulfate dihydrate, which is gypsum. This material readily dewateres, and there are systems in use where the slurry is transported to a pond and construction equipment is used to excavate and stockpile the gypsum. The production of commercial-grade FGD gypsum used for wallboard manufacturing usually requires forced oxidation in the scrubbers or external to the scrubbers and dewatering by filtration equipment such as vacuum filters or centrifuges and sedimentation ponds. The dry material from dry scrubbers that is captured in a baghouse along with fly ash consists of a mixture of sulfites and sulfates in addition to fly ash. This powdered material is referred to as dry FGD ash, dry FGD material, lime spray dryer ash, lime spray dryer, or lime spray dryer residue.

FGD material dry scrubbers – the dry powdered material from dry scrubbers that is collected in a baghouse along with fly ash and consists of a mixture of sulfites, sulfates, and fly ash.

FGD products – another term for the by-products from wet and dry FGD systems.

FGD sludge – another name for scrubber sludge wet FGD material or filter cake. See **wet FGD material**.

Filter cake – the material produced by filtering equipment such as vacuum filters for dewatering wet FGD material. See **wet FGD material**.

Fixated FGD material – a designed mixture of dewatered FGD sludge (also known as scrubber sludge or filter cake) which is primarily calcium sulfite with either a low-lime (Class F) fly ash and lime with a high-lime fly ash (Class C) or with a low-lime fly ash and a cementitious material such as cement kiln dust, lime kiln dust, or fluidized-bed combustion ash. The designed mixture is produced in a mixing facility sometimes referred to as a sludge treatment plant, and transported by belt conveyor to an area where it is stockpiled for a number of hours or days to undergo an initial chemical set. The stockpiled material is then excavated and loaded onto trucks or other earthmoving equipment for placement as a fill in beneficial use applications or for placement in a landfill for storage or disposal, where it undergoes a further chemical set. After placement, the fixated material forms a stable, monolithic mass of low permeability.

Fixated scrubber sludge – another name for fixated FGD material.

Flue gas desulfurization – removal of gaseous sulfur dioxide from boiler exhaust gas. Primary types of FGD processes are wet scrubbers, dry scrubbers, and sorbent injection. Sorbents include lime, limestone, sodium-based compounds, and high-calcium coal fly ash.

Forced oxidation – a process employed to supply additional air in wet FGD systems, resulting in a predominantly calcium sulfate dihydrate (gypsum) by-product with improved storage characteristics as well as greater commercial potential.

In situ oxidation (wet FGD) – a process in which both SO₂ absorption and oxidation are carried out within the scrubber.

Lime spray dryer ash – the residue from a spray dryer FGD system. The resulting by-product is dried by the heat of the flue gas and collected in a particulate control device with the fly ash. See **dry FGD material**.

Lime spray dryer residue – another name for lime spray dryer ash.

Scrubber – any of several forms of chemical/physical devices that remove sulfur compounds formed during coal combustion and especially from coal-fired power plants. See **wet FGD**.

Scrubber sludge – another name for wet FGD material. See **wet FGD material**.

Spray dryer – a type of dry FGD system. See **dry FGD**.

Stabilized FGD material – another name for fixated FGD material. See **fixated FGD material**.

Wet FGD – an FGD system which uses a wet scrubber to introduce an aqueous solution of either slaked lime (calcium hydroxide) or limestone (principally calcium carbonate) into the flue gas in a spray tower. The sorbent reacts with or oxidizes the sulfur dioxide in the flue gas and converts it to a by-product that is referred to as scrubber sludge, scrubber material, or wet FGD material.

Wet FGD material – the by-product of wet FGD processes or systems. It is composed primarily of water, calcium sulfite/sulfate solids, and small quantities of fly ash. It has the consistency of a sludge when allowed to settle in a pond or when the water is removed by filtering equipment such as vacuum filters. It is commonly referred to as scrubber sludge. Depending on the composition of the injected lime or limestone, some by-products will also contain magnesium sulfite and/or sulfate and possibly traces of barium sulfite or boron in addition to some trace metals.